THE M.K.S. SYSTEM OF UNITS*

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GLOSSARY OF ABBREVIATIONS

I.E.C.	International Electrotechnical Commission.
B.A.	British Association for the Advancement of Science.
I.P.U.	International Union of Pure and Applied Physics.
S.U.N. Committee.	Committee on Symbols, Units, and Nomenclature of the I.P.U.
N.P.L.	National Physical Laboratory (British).
E.M.M.U. Committee.	Electric and Magnetic Magnitudes and Units Committee of the I.E.C.
I.C.W.M.	International Committee of Weights and Measures.
C.C.E.	Comité Consultatif d'Électricité of the I.C.W.M.
m.k.s.	metre-kilogramme-second (system).
c.g.s.	centimetre-gramme-second (system).
f.g.s.	foot-grain-second (system).
m.g.s.	metre-gramme-second (system).
m.m.s.	millimetre-milligramme-second (system).
q.e.s.	(earth - quadrant) - (eleventh - gramme) second (system).
c.g-s.s.	centimetre - (gramme - seven) - second (system).

INTRODUCTION

As is well known, the International Electrotechnical Commission is an international organization maintained by 25 countries. It was called into existence under the leadership of R. E. Crompton, in response to a recommendation of the International Electrical Congress of St. Louis (Mo.) in 1904. It was organized in 1906 with its secretariat in London, and C. Le Maistre has been its general secretary since that time. It comprises 24 advisory committees, each dealing with a particular electrotechnical subject, and it has held plenary meetings at London, Paris, Brussels, The Hague, Berlin, Cologne, Turin, Zurich, Bellagio, Rome, Geneva, Copenhagen, Stockholm, Oslo, and New York. It has accomplished much international electrotechnical work during its 29 years of activity.

At its plenary meeting, in June, 1935, at Scheveningen-Bruxelles, the I.E.C. unanimously adopted the Giorgi System of metre-kilogramme-second (m.k.s.) units, 15 countries being represented by the delegates present. Every electrical engineer should make himself acquainted with the significance of this decision. In effect, it replaces the three systems at present in use (namely, the absolute electromagnetic c.g.s. system, the absolute electrostatic c.g.s. system, and the practical series) by one practical system.

The fundamental units are so chosen that the present practical series or system becomes at once an absolute system. This brings about a great simplification in the teaching of units and in practical calculations.

For the present, the question of rationalization has been left for future consideration. As the permeability and permittivity of space are no longer unity, it would be an easy matter to fix their values so as to rationalize all calculations; that is to say, to arrange matters so that the multiplier 4π comes into those formulæ only where it would be expected to enter.

Not since the International Congress of Electricians at Paris in 1881,† has there been made a decision of similar international significance. It is the purpose of this paper to outline the principal historical antecedents of this I.E.C. action, to indicate its main import to electrical engineering, and to suggest a few of the implications it may involve. The account here given is, however, necessarily subsidiary to the official minutes of the meeting, which should be consulted by interested readers.

HISTORY OF C.G.S. AND PRACTICAL UNITS

As early as 1848, resistance boxes had been produced in Germany, calibrated to correspond to the linear resistance of particular sizes of telegraph wire. Gauss and Weber, about 1850, showed how to make certain electric and magnetic measurements in absolute measure, adopting for this purpose the millimetre-milligramme-second system (m.m.s.). In 1860, Werner Siemens introduced his mercury unit of resistance, i.e. a glass tube of 1 mm^2 cross-sectional area and 1 m long, filled with pure mercury, at 0° C.

The British Association for the Advancement of Science (commonly abbreviated to B.A.), at its meeting in Manchester, in 1861, established a committee to report upon "standards of electrical resistance." This B.A. committee became famous for its pioneer work. It made annual reports‡ until 1870, and from 1881 until 1912. During the second period Lord Rayleigh was its chairman and Sir Richard Glazebrook its secretary.§ It recommended the adoption of an absolute fundamental system of scientific units, and after trying the foot-grain-second system (f.g.s.) advocated the metre-gramme-second system (m.g.s.). It computed theoretically, and worked out practically, approximate electrical standards, especially that of electrical resistance, for which Latimer Clark suggested the name "ohm." Because the m.g.s.

* Also see page 245.

The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† See Reference (7). ‡ *Ibid.*, (1). § *Ibid.*, (1a).

absolute electromagnetic unit of resistance was found to be an extremely small quantity in reference to practical needs, this committee recommended that the practical unit of resistance (or ohm) should be 10^7 of these units, since 10 such ohms would be roughly equal to the resistance of 1 mile of an ordinary size of telegraph wire. Telegraph engineering was at that date almost the only existing application of electrical science. The demand for electrical units came from telegraph engineers. Again, since the m.g.s. electromagnetic unit of electromotive force was extremely small from a telegraph-engineering standpoint, another large decimal multiple, 10^5, was recommended for the practical unit, with the name "volt," since about 100 000 such m.g.s. units were roughly equal to the electromotive force of one Daniell voltaic cell. The decimal factors 10^7 and 10^5 were purely arbitrary and adventitious, to meet the needs and convenience of these particular applications; but once the volt and ohm were adopted, a new strong influence came into effect, namely, systematic connection between the practical units, such, for example, that the volt acting in a circuit of 1 ohm should deliver 1 practical unit of current. This would mean that the rest of the practical units were no longer arbitrary, but assigned themselves in accordance with the laws of physics, in 1-to-1 unit relations. Thus the literature shows that the original value of the farad, as the B.A. practical unit of capacitance, was equal to what is now called the "microfarad," taken as an arbitrary convenient magnitude for telegraph practice; but this was changed* later to the present magnitude of the "farad," because of considerations of systematic relations.

The second B.A. committee was appointed in 1868, "for the selection and nomenclature of dynamical and electrical units." It proceeded to discuss and compare the relative advantages of the c.g.s., m.g.s., f.g.s., and m.m.s. systems, for the purposes of a comprehensive fundamental system adapted for use in all branches of science. Its first report—an important document—was published† in 1873. It decided, after much debate, in favour of the c.g.s. system. A principal reason for this choice was that the c.g.s. system was the only one of the four considered that gave the unit of density equal to that of pure water at standard temperature and pressure (1 gramme per cm^3). The practical units with standards already in use among practitioners—ohm, volt, and farad—were converted from the m.g.s. multipliers 10^7, 10^5, and 10^{-7}, to the corresponding c.g.s. multipliers 10^9, 10^8, and 10^{-9}, as they exist to-day. The report also advocated three names for as many c.g.s. units, namely, the "dyne" for unit force, the "erg" for unit work, and the "erg per second" for unit power. These names also remain in use.

Although the c.g.s. system and its appended practical units gained recognition among scientists and electrotechnicians, no international action was taken on them until the First Electrical Congress at Paris, in 1881. This memorable Congress‡ adopted the c.g.s. electromagnetic units as fundamental, and five practical units decimally derived therefrom: the ohm, volt, ampere, coulomb, and farad. Steps were taken to produce a standard ohm as a mercury column resistor of 1 mm^2 cross-section at standard temperature and pressure. The five practical units formed a series in 1-to-1 relation. The c.g.s. system thus became the great fundamental absolute system for universal measurements in all branches of physical science.

* See Reference (2). † *Ibid.*, (3). ‡ *Ibid.*, (7).

Since 1881, four more units have been added to the practical electrical series: the joule, watt, henry, and weber, in 1889, 1889, 1893, and 1933, respectively, the first three at international electrical congresses, and the fourth by the I.E.C. at Paris (confirmed this year at Brussels).

COMPREHENSIVE PRACTICAL UNIT SYSTEMS

Clerk Maxwell, who placed the classical c.g.s. systems (electric and magnetic) on a firm mathematical basis, pointed out* in 1881, that the practical series of electromagnetic units virtually formed a complete electromagnetic system, in which the unit of length was the earth-quadrant (10^9 cm), the unit of mass 10^{-11} gramme (eleventh-gramme), and the unit of time the mean solar second. The numerical value of space permeability in this q.e.s. system of Maxwell was $\mu_0 = 1$, the same as in the c.g.s. magnetic system. This conception of the practical series as part of a magnetic system was interesting, but merely a proposition in the theory of units. Neither Maxwell nor any other theorist ever seriously proposed that the q.e.s. system should be adopted in practical scientific work, because the fundamental units of length and mass were so awkward. For instance, with unit electric current strength as 1 ampere, the unit of current density would be the ampere per square earth quadrant! Maxwell's discovery remained, therefore, an academic curiosity.

G. Giorgi of Rome pointed out,† in 1901, that if the value of space permeability μ_0 were taken not as unity but as 10^{-7} unrationalized, or as $4\pi \times 10^{-7}$ rationalized, the practical series fell into an electromagnetic system like the q.e.s. system, and parallel to the magnetic c.g.s. system, with unit length equal to the international metre (10^2 cm), unit mass equal to the kilogramme, and unit time the mean solar second. Giorgi presented a paper on this new m.k.s. system to the International Electrical Congress‡ of St. Louis, in 1904. A colleague of his, Ascoli, presented another paper§ to the St. Louis Congress, pointing out that there existed an indefinitely long series of such systems, all containing the practical series of units, such that if the system length unit were 10^l cm and its mass unit 10^m grammes, then the equation of condition was $2l + m = 7$. In Giorgi's m.k.s. system, $l = 2$ and $m = 3$: while in Maxwell's q.e.s. system, $l = 9$ and $m = -11$. In this indefinite series of possible systems, all embracing the internationally adopted practical units, only Maxwell's q.e.s. system kept $\mu_0 = 1$, and only Giorgi's m.k.s. system comprised the international standards of length and mass maintained by the International Bureau of Weights and Measures at Sèvres, in the Park of St. Cloud, near Paris. Moreover, only Giorgi's m.k.s. system offered units of length and mass that were satisfactory practically.

The Giorgi m.k.s. system slowly advanced in favour all over the world. It was endorsed by several physicists in Europe. In the United States, G. A. Campbell

* See Reference (6). † *Ibid.*, (12). ‡ *Ibid.*, (15). § *Ibid.*, (14).

came forward* heartily in support of the "definitive system," which differs from the Giorgi system only in details of definition. The only seriously-advanced objection to it, setting aside the complaint that the Giorgi system fundamental equations are dissymmetrical from the standpoint of theoretical physics, seems to have been that its unit of density is the kilogramme per cubic metre, which is 1 000 times smaller than that of pure water under standard specifications. Since the recent discoveries, however, of deuterium and of "heavy water," the argument for unit-density water has lost some force. To have the density of distilled water unity is, of course, an asset to a system of units; but its loss is not disastrous. The great bulk of water on the earth is ocean water, with a density distinctly greater than that of 1 gramme per cm^3; moreover, tables of specific gravity with that of pure water taken as unity, are the same in the m.k.s. system as in the c.g.s. system, and for engineering purposes specific gravities are likely to be more useful than absolute densities.

In or about the year 1916, proposals appeared to adopt another comprehensive system, sometimes† called "international system," based upon the cm as length unit, the gramme-seven or 10^7 grammes (10 metric tons) as mass unit, and the mean solar second as the unit of time (c.g-s.s. system). Here $l = 0$ and $m = 7$. Several proponents have been named for this system, among them Blondel, Dellinger, Bennett, Karapetoff, and Mie. In the c.g-s.s. system, the numerical value of space permeability μ_0 would be 10^{-9} unrationalized, and $4\pi \times 10^{-9}$ rationalized. Various papers and at least one book‡ have been printed on this system, which claimed many of the advantages of the Giorgi system. Its principal disadvantage, however, was the awkwardly large size of its unit of mass.

MAGNETIC UNITS

In reference to the history of practical magnetic units, it may suffice here to point out that, as early as 1889, the Second Electrical Congress of Paris discussed the adoption of units for magnetic flux and flux density in the practical system, with personal names for both; but no action was taken in the matter at that time. Similar suggestions were made at the Third International Electrical Congress, of Frankfort, in 1891, but again without action being taken. At the Fourth International Electrical Congress, of Chicago, in 1893, certain proposals of the American I.E.E., to adopt magnetic units in the practical series for magnetomotive force, flux, flux density, and reluctance, were considered; but the chamber of delegates recommended§ that magnetic units should be restricted to the c.g.s. system, and without specific names.

At the Fifth International Electrical Congress, of 1900, in Paris, names were requested for c.g.s. magnetic units. There was considerable difference of opinion, and debate. Finally the Congress adopted the names "maxwell" for the c.g.s. unit of magnetic flux, and "gauss" for the c.g.s. unit of magnetizing force H. There was also some accidental misunderstanding of the action taken, some of the delegates present having supposed that the name "gauss" had been adopted for flux density B. No further international action on magnetic units took place thereafter, until the matter was taken up in 1927 by the I.E.C.

Actions of the I.E.C. and the International Union of Pure and Applied Physics (I.P.U.), in Reference to Magnetic Units

At its Bellagio* meeting in 1927 the I.E.C. discussed certain proposals relating to magnetic units. In view of much manifest difference of opinion, a sub-committee was appointed to consider and report upon the subject. The committee, composed of representatives from different countries, endeavoured to reach conclusions by correspondence; but this was found to be impracticable because of the marked differences of opinion as to the meaning of terms used in magnetic literature, and especially as to the meaning of the unit name "gauss." These differences affected not only the literature of different countries, but also of different writers in each of several countries. The matter therefore was brought to the attention of the various I.E.C. national committees and placed on the agenda of the next I.E.C. meeting, in Scandinavia (1930).

After considerable discussion in Copenhagen and Stockholm, the committee decided unanimously† that, for electrotechnical purposes, the convention should be established that, in free space, the quantities flux density B and magnetizing force H should be taken as physically different; so that their ratio, the space permeability μ_0, was a physical quantity with dimensions and not a mere numeric. The same convention was applied to the absolute permeability μ of a simple magnetic medium; so that its relative permeability μ/μ_0 was dimensionless, or a mere numeric. The committee then assigned the unit name "gauss" to flux density B, confirmed the name "maxwell" for magnetic flux Φ and gave the new international name "oersted" to the unit of magnetizing force H, all in the classical c.g.s. system. These recommendations were confirmed unanimously by the I.E.C. plenary convention at Oslo, in July, 1930. This Oslo convention gave satisfaction to the great majority of electrotechnicians all over the world; but the satisfaction among physicists has been less complete.

The International Union of Pure and Applied Physics (I.P.U.), at its Brussels meeting of July, 1931, appointed, for the first time, a committee on "symbols, units, and nomenclature" (S.U.N.). This important S.U.N. Committee has held several meetings of great value to the physical sciences. Its president has been Sir Richard Glazebrook, and its secretary, E. Griffiths, of the National Physical Laboratory (N.P.L.). The I.E.C. requested the I.P.U. for the co-operation of the S.U.N. Committee in the matter of magnetic units, and this co-operation very courteously was granted. The S.U.N. Committee proceeded to prepare a questionnaire on "electrical units," addressed to physicists and physical societies in different countries, calling attention to certain ambiguities in the definitions of fundamental electric and magnetic qualities entering into the classical c.g.s. system, and inviting opinions as to how these ambiguities might be eliminated, in order to arrive at international agreement. This

* See Reference (24). † *Ibid.*, (21). ‡ *Ibid.*, (22). § *Ibid.*, (9).

* See Reference (25). † *Ibid.*, (28).

printed document* was issued by the S.U.N. Committee in December, 1931, and replies thereto were collected and distributed to the I.P.U. committees, as well as to the national committees of the I.E.C.

The electric and magnetic magnitudes and units (E.M.M.U.) Committee of the I.E.C. met at London in September, 1931, to consider the Oslo recommendations made by the same committee in July, 1930. Ten countries were represented by delegates. The president and secretary of the S.U.N. Committee attended the meeting, as well as H. Abraham (general secretary of the I.P.U.), A. F. Enström (president of the I.E.C.), and C. Le Maistre (general secretary of the I.E.C.). At this meeting the actions taken at Oslo in regard to c.g.s. magnetic units were endorsed unanimously.

In view of the many physicists assembling in Paris during the week July 5–12, 1932, to attend the 1932 Paris International Electrical Congress, the S.U.N. Committee called an informal meeting in Paris on July 9, to discuss the matters contained in its questionnaire, and especially the c.g.s. magnetic units. Sir Richard Glazebrook was the chairman, and E. Griffiths was the secretary; 19 persons, from 8 countries, attended. The actions taken were informal, in the sense that the voting was by individuals and not by countries. The resolutions adopted, if not unanimous, were by considerable majorities. Among the resolutions was the proposition (6) "B and H are quantities of different nature." The Oslo convention was endorsed, and the I.E.C. actions concerning c.g.s. magnetic units and their names were confirmed. No specific reference was made to the Giorgi system; but it was voted that: "(1) Any system of units recommended must retain the 8 internationally recognized practical units: joule, watt, coulomb, ampere, ohm, volt, farad, henry." It was voted also that in any practical magnetic system, "the factor $4\pi/10$ should be retained in the definition of magnetomotive force." This implies that the S.U.N. Committee opposed rationalizing the practical magnetic system.

At the Brussels meeting of the I.P.U. in July, 1931, already mentioned, R. A. Millikan was elected as the incoming president, and it was contemplated holding the next I.P.U. meeting at Chicago in June, 1933, contemporaneously with the Chicago Exposition of 1933. It was found necessary, however, to postpone the I.P.U. meeting; but a meeting of the American Section of the I.P.U., with a few foreign guests, was held at Chicago instead, June 24, 1933, in Mandel Hall, University of Chicago. R. A. Millikan, president of the I.P.U., opened the meeting. The programme was directed to the work of the international S.U.N. Committee, and six papers were read, with E. C. Crittenden, chairman of the American S.U.N. Committee in the chair. The papers† related to electric and magnetic units and systems, as prepared by Sir Richard Glazebrook, H. Abraham, L. Page, G. A. Campbell, H. L. Curtis, and A. E. Kennelly. E. Bennett acted as secretary of the meeting. The attendance at the meeting was about 150, and of these the estimated number voting was 30 to 40. In brief, the following resolutions‡ were passed:—

(1) That the classical c.g.s. system should be left unchanged.

(2) That the existing series of practical units may advantageously be extended into a complete absolute practical system, either through the m.k.s. system, or through the c.g.-s.s. system; of these, the m.k.s. system is preferred.

(3) That the American S.U.N. Committee shall be requested to consider the objections to the use of the absolute ohm and the advantage that might be gained by the use of the international ohm in the practical system.

A meeting of the E.M.M.U. Committee of the I.E.C. was held* at Paris in October, 1933. The "weber" was adopted as the practical unit of magnetic flux Φ subject to the approval of the various national committees. The names "hertz" and "siemens" likewise were voted for the names of the practical units of frequency and conductance respectively. The Oslo convention concerning μ_0 and μ was reconfirmed. Special consideration was given to the resolutions passed by the American Section of the I.P.U. at Chicago in June, 1933, on the extension of the practical series of units into a complete system, as referred to in preceding paragraphs. Giorgi, who was present as an Italian representative, gave a brief résumé of the m.k.s. system. H. Abraham, general secretary of the I.P.U., who attended the meeting, pointed out certain advantages of the m.k.s. system, as also did M. Brylinski, president of the French I.E.C. national committee. The following resolution was adopted unanimously:—

"Section B of the Advisory Committee No. 1 on nomenclature, having heard with great interest the communication from Mr. Giorgi on the m.k.s. system, and endorsing the resolution adopted by the American Section of the International Union of Pure and Applied Physics at Chicago, in June, 1933, decides to invite the national committees to give their opinion on the extension of the series of practical units at present employed in electrotechnics by its incorporation in a coherent system having as fundamental units of length, mass, and time, the metre, kilogramme, and second, and as fourth unit either that of resistance expressed as the precise multiple 10^9 of c.g.s. electromagnetic unit or the corresponding value of the space permeability of a vacuum."

These resolutions were distributed to all the I.E.C. national committees in the regular way, together with the minutes of the meeting, with a request for opinions.

The I.P.U. held an important General Meeting at London in October, 1934, attended by about 600 members and visitors. Meetings of the S.U.N. Committee were held at this time and a Report† was unanimously approved, endorsing the resolutions of the informal Paris Conference of 1932, with an appended Table of electromagnetic units.

ACTIONS OF THE I.E.C. AT THE LATEST AND PLENARY MEETING AT SCHEVENINGEN-BRUSSELS

In regard to actions on units, the E.M.M.U. Committee met at Scheveningen, with representatives from 15 countries. President Enström attended the sessions.

* See Reference (40). † Ibid., (49). ‡ Ibid., (49)–(53).

* See Reference (54). † Ibid., (59a).

Paul Janet, president of Advisory Committee No. 1, was prevented from being present. He was unanimously elected honorary president of the I.E.C., an honour shared by Elihu Thomson. The principal actions taken at this meeting were briefly as follows:—

(1) The Oslo convention concerning μ_0 and μ was reconfirmed.

(2) The adoption of the "weber" was confirmed as the name of the practical unit of magnetic flux Φ.

(3) The replies were read as received from the various national committees concerning the extension of the practical series into a practical system of units on the m.k.s. basis. Practically all the replies were in favour. The question of adopting the m.k.s. system was then moved and unanimously approved, except that two countries made reservations as to the suitability of retaining the kilogramme as a basic unit of the system.

There was considerable difference of opinion among the delegates as to the fourth fundamental unit for the system. The ohm and the coulomb each had been suggested. It was agreed that a fourth unit was needed, because it would be possible, starting with the three units, metre, kilogramme, and second, to construct an indefinite number of possible associated electromagnetic series, differing from the existing practical series which all desired to maintain. It was finally agreed to defer action on the choice of a fourth fundamental unit until an opportunity had been offered to consult the Comité Consultatif d'Electricité (C.C.E.) of the International Committee of Weights and Measures (I.C.W.M.) at Sèvres, and also the S.U.N. Committee of the I.P.U. In the meantime, it was voted that the new system should be called the "Giorgi system." Opinions were also requested from the various national committees as to the selection of the fourth unit.

(4) By way of example, in the formation of derived units in the system, the following were adopted unanimously: (*a*) the "volt per metre" as unit of electric force; (*b*) the "weber per square metre" as unit of magnetic flux density B; (*c*) the "joule per cubic metre" as unit of volume energy.

(5) The actions taken at the preceding meeting in Paris, concerning the practical unit names "hertz" and "siemens" were confirmed, as also the desirability of inserting the space permeability symbol μ_0 in all working magnetic formulæ where its absence might mislead, thus reconfirming the Oslo convention.

ADVANTAGES OF THE GIORGI SYSTEM TO STUDENTS OF ELECTRICAL ENGINEERING

Table 1, which gives a list of m.k.s. and c.g.s. units, shows that although the classical c.g.s. system is in no way altered or disturbed by the completion of the practical series into an independent practical system, yet:

(1) There is great simplification in elimination of the necessity for learning the decimal ratios 10^0, 10^8, 10^7, 10^{-1}, and 10^{-9}, which connect various units in the two systems. The practical units all stand in unity-sequence relation.

(2) The m.k.s. system is single and requires no accompanying companion electrostatic system. All electrostatic phenomena can be dealt with very easily through the existing electromagnetic practical units.

(3) The dimensional formulæ of the Giorgi units can be expressed without resorting to fractional exponents, as shown by Giorgi* and other writers.

(4) It permits the use of either "rationalized" or "unrationalized" formulæ, according to the choice of each writer, without disrupting the system on that account.

(5) It requires no appreciable change in the existing literature and terminology of electric circuits. It may be said that the electrical engineering literature of the voltaic circuit is already Giorgian. It will not be difficult to transform the literature of the magnetic circuit from c.g.s. to m.k.s. units.

(6) For almost all practical purposes, the m.k.s. system can be studied and used now, without waiting for the formal adoption of the fourth fundamental unit to complete the system's base. Until readers become familiar with the expression of magnetic circuit formulæ in m.k.s. units, the old c.g.s. magnetic formulæ may be retained in the c.g.s. system without confusion.

(7) It affords a clear perspective of the distinction between the earlier c.g.s. units and the practical units, in regard to nomenclature and scope. If new c.g.s. units be named, the names may conformably be impersonal. New practical units may conformably receive personal names, especially units 12, 13, and 16, in Table 1. If desired, a few impersonal names in the m.k.s. system might be changed later into personal names.

COMMENTS

Table 1 shows that the only department of the c.g.s. system in which personal names appear is that concerning the magnetic circuit. This discrepancy results from the resolution of the Chicago Congress of 1893 to keep magnetic units out of the practical series. The very large aggregate number of electrotechnicians all over the world were thus impelled to seek for the magnetic circuit names they so earnestly desired, in the c.g.s. system itself. Although this inconsistency is regrettable, it seems likely that, with patience and good will, it may be surmounted later.

Looking back upon the path of the development of units since 1861, when the B.A. made the first move in the direction of practical units, it appears that starting in about 1865 with the ohm and the volt based upon the c.g.s. system, and with magnitudes selected fortuitously to suit the convenience of electric telegraphy, Ohm's law pointed the way from these two nuclei to the coherent magnitude of the ampere as the practical unit of current. These, in turn, led, through other simple physical laws, and their mathematical formulæ, to the succeeding members of the practical series. After the ohm and volt, no further arbitrary choice was left, and the practical series determined itself. Each new member of the series made systematization more imperative and finally led to the completion of the whole series into the Giorgi system. It has been as though the marvellous simplicity of the physical universe in its individual actions, working on the minds of men engaged in physical applications, brought pressure upon them

* See Reference (55).

Table 1

INCOMPLETE LIST OF M.K.S. UNITS AND OF CORRESPONDING C.G.S. UNITS

Number	Quantity	Symbol	M.K.S. unit	C.G.S. unit	C.G.S. units in one m.k.s. unit
Mechanical					
1	Length	L	metre	centimetre	10^2
2	Mass	M	kilogramme	gramme	10^3
3	Time	T	second	second	1
4	Area	S	square metre	square centimetre	10^4
5	Volume	V	cubic metre (stere)	cubic centimetre	10^6
6	Frequency	f	hertz (cycle per second)	cycle per second	1
7	Density	d	kilogramme per metre	gramme per cubic centimetre	10^{-3}
8	Specific gravity		numeric	numeric	1
9	Velocity	v	metre per second	centimetre per second	10^2
10	Slowness		second per metre	second per centimetre	10^{-2}
11	Acceleration	a	metre per second per second	centimetre per second per second	10^2
12	Force	F	— (joule per metre)	dyne	10^5
13	Pressure	p	— (joule per cubic metre)	dyne per square centimetre, barye	10
14	Angle	α, β	radian	radian	1
15	Angular velocity	ω	radian per second	radian per second	1
16	Torque	τ	— (joule per radian)	dyne $\perp$ centimetre	10^7
17	Moment of inertia	J	kilogramme-square metre	gramme-square centimetre	10^7
Energetics					
18	Work or energy	W	joule	erg	10^7
19	Angular work, τa	W	joule	erg	10^7
20	Volume energy	w	joule per cubic metre	erg per cubic centimetre	10
21	Active power	P	watt	erg per second	10^7
22	Reactive power	jQ	var	erg per second	10^7
23	Vector power, $P \pm jQ$		watt $\angle$	erg per second	10^7
Thermal					
24	Quantity of heat	Q	kilogramme-calorie	gramme-calorie	10^3
25	Temperature	θ	degree Centigrade or Kelvin	degree Centigrade or Kelvin	1
Luminous					
26	Intensity	I	candle	candle	1
27	Luminous flux	ψ	lumen	lumen	1
28	Illumination	E	lux	phot	10^{-4}
29	Brightness	b	candle per square metre	stilb	10^{-4}
30	Focal power		diopter		10^{-2}
Electrical					
31	Electromotive force	E	volt		10^8
32	Potential gradient	ϵ	volt per metre		10^6
33	Resistance	R	ohm		10^9
34	Resistivity	ρ	ohm-metre		10^{11}
35	Conductance	G	siemens, mho		10^{-9}
36	Conductivity	γ	siemens per metre, mho per metre		10^{-11}
37	Reactance	jX	ohm		10^9
38	Impedance, $R \pm jX$	Z	ohm $\angle$		10^9
39	Quantity	Q	coulomb		10^{-1}
40	Displacement	Q	coulomb		10^{-1}
41	Current	I	ampere		10^{-1}
42	Current density	i	ampere per square metre		10^{-5}
43	Capacitance	C	farad		10^{-9}
44	Specific inductive capacity	ϵ/ϵ_0	numeric	numeric	1
Magnetic					
45	Magnetic flux	ϕ	weber	maxwell	10^8
46	Flux density	B	weber per square metre	gauss	10^4
47	Inductance	L	henry		10^9
48	Relative permeability	μ/μ_0	numeric	numeric	1

NOTE.—Various units used in acoustical engineering, radio engineering, and mechanical engineering, are omitted from this list.

psychologically, to imitate in their thoughts and arithmetic the order and system of the vast environment in the physical world. In 1935, the need for the system has reached the stage of international recognition, over a journey of 70 years. Under unfavourable conditions, the time required might have been much greater.

Table 1 also suggests the importance of co-operation among all scientific organizations, national as well as international, to maintain the systematic quality and classification of all units they employ. In a structure like the m.k.s. system there can logically be one and only one unit for each physical quantity.

In regard to the rationalization or non-rationalization of the m.k.s. system, discussions on the subject in recent years by the I.E.C. and I.P.U. committees have shown that there is much difference of opinion on the subject. In the E.M.M.U. Committee a small majority has been in favour of rationalization; in the S.U.N. Committee the majority has been more definitely against it. It is clear that any attempt to force a decision one way or the other at the present time would divide the m.k.s. adherents into two opposing camps, the rationalists and the non-rationalists. It seems desirable, therefore, to avoid the issue and to leave each writer free to follow his own choice, until experience may have crystallized opinion in the different countries. The same question pervades the c.g.s. world to-day. The classical c.g.s. electric and magnetic systems of Maxwell are unrationalized, while the Heaviside–Lorentz modification is rationalized. The advantages of rationalizing would be that the m.k.s. system would thus be made simpler, more logical, and coherent. There is much to be said for having pole strength identical with magnetic flux, so that a pole of 1 weber would give emergence to 1 weber of flux, and a charge of 1 coulomb also give emergence to 1 coulomb of electric flux. Table 2 shows that there are already enough practical international quantities to give names to all the principal units in the rationalized magnetic circuit, although some of them are cumbersome; whereas it appears to be necessary to adopt a series of new international names, in order to provide for the corresponding needs of the unrationalized circuit. Giorgi himself, in proposing his system (1901–04), rationalized it, as an act of recommendation. On the other hand, the disadvantage of rationalizing the m.k.s. system would be to break parallelism, in this direction, with the parent classical c.g.s. system.

As regards the fundamental basis of the m.k.s. system, it has been pointed out by several writers that it is a blemish on the system to have (in the *kilo*gramme) a basic prefixed unit. The m.k.s. "metre" is certainly preferable to the c.g.s. "centimetre" in this respect; but the m.k.s. "kilogramme" is inferior to the c.g.s. "gramme." Theoretically, the basic units of any system should be prefix-free. However, the c.g.s. system has given splendid service to the world of science for many years, in spite of the "centimetre."

Until there has been time to obtain the opinions of the I.C.W.M. and the I.P.U. on the question of choosing the fourth fundamental unit for the m.k.s. system, it would be invidious to offer any views on that point. It may be permissible to point out at this time, however, that whatever particular fourth unit may be selected in drawing up the international constitution of the Giorgi system, it is very desirable that each and all of the practical units in the ohm-volt-ampere series shall be identical for both basic and applied physicists. It would surely be a great mis-

Table 2

Electric and Magnetic M.K.S. Units Affected by the Deferred Question of Rationalization

Number	Quantity	Symbol	Name of rationalized* m.k.s. unit	Unrationalized units in one rationalized unit
Electrical				
49	Electric flux	ψ	coulomb	
50	Flux density	D	coulomb per square metre	
51	Space permittivity	ϵ_0	farad per metre	
52	Space elasticity	σ_0	metre per farad	
53	Elastance	S	daraf	
Magnetic				
54	Magnetomotive force	$\mathfrak{F}$ or M	ampere-turn	4π
55	Magnetizing force	H	ampere-turn per metre	4π
56	Space permeability	μ_0	henry per metre	$1/4\pi$
57	Space reluctivity	ν_0	metre per henry	4π
58	Permeance	$\mathfrak{P}$	weber per ampere-turn	$1/4\pi$
59	Reluctance	$\mathfrak{R}$	ampere-turn per weber	4π
60	Pole strength	m	weber	$1/4\pi$
61	Magnetic moment (ml)	$\mathfrak{M}$	weber-metre	$1/4\pi$
62	Magnetization	$\mathcal{J}$	weber per square metre	$1/4\pi$

* No names have been chosen for unrationalized units.

fortune to the whole scientific world if in taking up a a standard ohm coil, or a standard capacitor, say 20 years hence, it should be necessary to ask whether it was standardized for physicists or electrotechnicians. Some trifling oversight in specifying the fourth fundamental unit might conceivably lead to such a divergence.

FURTHER DEVELOPMENTS

Since this paper was written in August, 1935, the following important developments have occurred in relation to the Giorgi system:—

(1) The Consultative Committee on Electricity (C.C.E.) of the International Committee on Weights and Measures (I.C.W.M.) held meetings at Paris-Sèvres, September 24–27, 1935, under the chairmanship of Paul Janet, and made an important report on electrical units and standards, covering also the reply to the I.E.C. inquiry concerning the fourth basic unit for the Giorgi system.

(2) The I.C.W.M. held meetings at Paris-Sèvres, October 1–8, 1935, adopting this C.C.E. report and authorizing its general publication. It also issued a brief statement for publication concerning its own activities and aims.

(3) The S.U.N. Committee under Sir Richard Glazebrook has been actively engaged in securing opinions, by correspondence, as to the fourth basic unit in the Giorgi system for reply to the I.E.C. question on that point. The reply is expected to be published shortly.

Table 3

NUMERICAL VALUES OF SPACE CONSTANTS IN M.K.S. SYSTEM, RATIONALIZED AND UNRATIONALIZED

Number	Quantity	Symbol	Rationalized	Unrationalized
Electrical				
51	Permittivity	ϵ_0	$10^7/4\pi c^2 = 8\cdot854 \times 10^{-12}$	$10^7/c^2 = 1\cdot113 \times 10^{-10}$
52	Elastivity	σ_0	$4\pi c^2/10^7 = 1\cdot129 \times 10^{11}$	$c^2/10^7 = 8\cdot988 \times 10^9$
Magnetic				
56	Permeability	μ_0	$4\pi \times 10^{-7} = 1\cdot257 \times 10^{-6}$	10^{-7}
57	Reluctivity	ν_0	$10^7/4\pi = 0\cdot7958 \times 10^6$	10^7

NOTE.—The value of the transmission velocity c is taken here as $2\cdot998 \times 10^8$ metres per second, and of c^2 as $8\cdot988 \times 10^{16}$ (metres per second)^2.

Because of admitted small discrepancies, of a few parts per myriad, between certain existing unit standards and their estimated absolute theoretical values, the future adoption of a fourth fundamental unit to complete the base of the m.k.s. system might alter slightly some of the numerical " constants " in Table 3.*

* See Reference (55).

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